Science for Every Teacher
Volume 1: Physics

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4. Explain what is meant by the statement, "a theory is a model."
5. Explain the role and importance of theories in scientific research.
6. Describe the possible implications of a negative experimental result. In other words, if the hypothesis is not confirmed, explain what this might imply about the experiment, the hypothesis or the theory itself.

About This Chapter

One cannot understand science, or make sense of scientific claims, without knowing about the *kind* of claims scientists make. In other words, to have an accurate understanding of what scientists mean when discussing a particular fact or theory, we need to understand the *nature* of scientific knowledge. So this is where we must begin.

Chapter 1
The Nature of Scientific Knowledge

To understand science correctly one needs to understand what we mean by scientific knowledge. Unfortunately, there is much confusion among non-scientists about the nature of scientific knowledge, and this confusion often leads to misunderstandings when we talk about scientific findings and scientific claims. This is nothing new. Misconceptions about scientific claims have plagued public discourse for thousands of years, and continue to do so to this day. This confusion is a severe problem, much written about within the scientific community in recent years.

Clearing up such misunderstandings is obviously an important issue in science education, for teachers and students alike. One of my hopes is that by helping to equip school teachers and parents with correct ways of talking about science, books like this one can help us begin to raise up generations of students who can avoid getting tangled up in the misunderstandings of past centuries, as well as the confusions that haunt us today. For this reason, each of the volumes in the *Science for Every Teacher* series begins with this same chapter.

To clear the air on this issue it is necessary to examine what we mean by the term *truth*, as well as the different ways we discover truth. Then we must discuss the specific characteristics of scientific knowledge, including the key scientific terms *fact*, *theory*, and *hypothesis*.

Whether you teach sixth grade or third grade or first grade, I would like you to stick with me for the next dozen-plus pages. Though it may look like we are about to jump into a college-level philosophical discussion, we aren't. We will keep it simple. But for reasons that should become clear as we go along, we need to begin our scientific study with a short lesson in *epistemology*. So we will begin by defining this term.

What is Truth and How Do We Know It?

Epistemology, one of the major branches of philosophy, is the study of what we can know and how we know it. Both philosophers and theologians claim to have important insights on the issue of knowing truth, and because of the roles science and religion have played in our culture over the centuries, we will need to look at what both philosophers and theologians have to say. The issue we need to treat briefly here is captured in this question: What is truth and how do we know it? In other words, what do we mean when we say something is *true*? And if we can agree on a definition for truth, how can we *know* whether or not something is true?

These are really complex questions, questions philosophers and theologians have been working on for thousands of years. But a few simple principles will be adequate for our purposes.

As for what truth is, my simple but practical definition is this:

Truth may be defined as *the way things really are*.

Whatever reality is like, that is the truth. If there *really* is life on other planets, then it is true to say, "There is life on other planets."

The harder question is that of how we can know the truth. Here the philosophical schools differ (no surprise there). But a mainstream approach that I find helpful claims there are two ways that we can know truth, and these involve either our senses or our use of reason. First, truths that are obvious to us just by looking around are said to be *evident*. It is evident that birds can fly. No proof is needed. So the proposition, "Birds can fly," conveys truth. Similarly, it is evident that humans can read books and that birds cannot. Naturally, when we speak of people knowing truth this way we are referring to people whose perceptive faculties are functioning normally.

The second way of knowing truth is through the valid use of logic. Logical conclusions are typically derived from a sequence of logical statements called a *syllogism*, in which two or more premises lead to a conclusion. For example, if we begin with the premises, "All dogs have four legs," and, "Buster is a dog," then it is a valid conclusion to state, "Buster has four legs." The truth of the conclusion of a logical syllogism clearly depends on the truth of the premises. The truth of the conclusion also depends on the syllogism having a valid structure. Some logical structures are not logically valid. (These invalid structures are called *logical fallacies*.) If the premises are true and the structure is valid, then the conclusion must be true.

Philosophy gives us two ways of knowing truth, by the direct testimony of our senses and by logical deduction from true premises.

So the philosophers provide us with two ways of knowing truth that most people agree upon—truths can be evident (according to our senses) or they can be proved (by valid use of reason from true premises).

The theologians in some faith traditions argue for an important third possibility for knowing truth, which is by revelation from supernatural agents such as God or angels. As obvious examples, Christians, Jews and Muslims believe that God has spoken to humans through prophets, and continues to speak to humans through the Bible, the Torah or the Koran. However, it is also obvious that not everyone accepts the possibility of knowing truth by revelation. Specifically, those who do not believe in God do not accept the possibility of revelations from God. Additionally, there are some who accept the existence of a transcendent power or being, but do

Theology argues that a third way of knowing truth is by revelation from God.

not accept the possibility of revelations of truth from that power. So this third way of knowing truth is embraced by many people, but certainly not by everyone.

Few people would deny that knowing truth is important. This is why we started our study by briefly exploring what truth is. But this is a book about science, and we need to move now to addressing a different question: What does *science* have to do with truth? The question is not as simple as it seems, as evidenced by the continuous disputes between religious and scientific communities stretching back over the past 700 years. To get at the relationship between science and truth, we will first look at the relationship between propositions and truth claims.

Propositions and Truth Claims

Not all that passes as valid knowledge can be regarded as *true*, which I defined in the previous section as "the way things really are." In many circumstances we do not actually *know* the way things really are. People do, of course, often use propositions or statements with the intention of conveying truth. But with other kinds of statements people intend to convey something else.

We will unpack this with a few example statements. Consider the following several propositions:

1. I have two arms.
2. My wife and I have three children.
3. I worked out at the gym last week.
4. My car is at the repair shop.
5. Texas gained its independence from Mexico in 1836.
6. Atoms are composed of three fundamental particles—protons, neutrons and electrons.
7. God made the world.

Among these seven statements are actually three different types of claims. From the discussion in the previous section you may already be able to spot two of them. But some of these statements do not fit into any of the categories we explored in our discussion of truth. We will discover some important aspects about these claims if we look at them one by one. So suppose for a moment that I, the writer, am the person asserting each of these statements as we examine the nature of the claim in each case.

I have two arms. This is true. I do have two arms, as is evident to everyone who sees me.

My wife and I have three children. This is true. To me it is just as evident as my two arms. I might also point out that it is true whether or not other people believe me when I say it. (Of course, someone could claim that I am delusional, but let's just keep it simple here and assume I am in normal possession of my faculties.) This bit about the statement being true regardless of others' acceptance of it comes up because of a slight difference here between the statement about children and the statement about arms. Anyone who looks at me will accept the truth that I have two arms. It will be evident, that is, obvious, to them. But the truth about my children is only really evident to a few people (my wife and I, and perhaps a few doctors and close family members). Nevertheless, the statement is true.

I worked out at the gym last week. This is also true; I did work out last week. The statement is evident to me, because I clearly remember going there. Of course, people besides myself must depend on me to know it, because they cannot know it directly for themselves unless they saw me there. Note that I cannot prove it is true. I can produce evidence, if needed, but the statement cannot be proved without appealing to premises that may or may not be true. Still, the statement is true.

My car is at the repair shop. Here is a statement that we cannot regard as a truth claim. It is merely a statement about where I understand my car to be at present, based on where I left it this morning and what the people at the shop told me they were going to do with it. For all I know, they may have taken my car joy riding, and it may presently be flying along the back roads of the Texas hill country. I *can* say that the statement is correct as far as I know.

Texas gained its independence from Mexico in 1836. We Texans were all taught this in school, and we believe it to be correct, but as with the previous statement we must stop short of calling this a truth claim. It is certainly a historical fact, based on a lot of historical evidence. The statement is correct as far as we know. But it is possible there is more to that story than we know at present (or will ever know).

Atoms are composed of three fundamental particles—protons, neutrons and electrons. This statement is, of course, a scientific fact. But like the previous two statements, this statement is not—surprise!—a truth claim. We simply do not know the truth about atoms. The truth about atoms is clearly not evident to our senses. We cannot guarantee the truth of any premises we might use to construct a logical proof about the insides of atoms, so proof will not be able to lead us to the truth. And as far as I know there are no supernatural agents who have revealed to us anything about atoms. So we have no access to knowing how atoms really are. What we do have are the data from many experiments, which may or may not tell the whole story. Atoms may have other components we don't know about yet. The best we can say about this statement is that it is correct as far as we know (that is, as far as the scientific community knows).

God made the world. This statement clearly is a truth claim, but people disagree on whether the statement is true or not. Many faith traditions assert that God did make the world, and many people accept this as the truth. Others do not. I include this example here because we will see soon what happens when scientific claims and religious truth claims get confused. Whether you teach in a public school, or a faith-based school, or a non-religious independent school, the issue is important. We all need to learn to speak correctly about the different claims people make.

To summarize this section, some statements we make are evidently or obviously true. But for many statements we must recognize that we don't know if they are actually *true* or not. The best we can say about these kinds of statements—and scientific facts are like this—is that they are correct as far as we know. Finally, there are metaphysical or religious statements about which people disagree; some claim they are true, some deny the same, and some say there is no way to know.

> With some statements we communicate truth. With other statements we communicate knowledge that is *correct as far as we know*. Scientific facts are of the second type.

Truth and Scientific Claims

Let's think a bit further about the truth of reality, both natural and supernatural. I think most people agree that regardless of what different people think about God and nature, there is some actual truth or *reality* about nature and the supernatural. Regarding nature, there is some full reality about the way, say, atoms are structured, whether we currently understand that structure correctly or not. As far as we know, this reality does not shift or change from day to day, at least not since the early history of the universe. So the reality about atoms—the truth about atoms—does not change.

And regarding the supernatural, there is some reality about the supernatural realm, whether anyone knows what that is or not. Whatever these realities are, they are *truths*, and these truths do not change, either.

Now, I have observed over the years that careful scientists do not refer to scientific claims as truth claims. They do not profess to knowing the ultimate truth about how nature *really* is. Instead, scientific claims are understood to be statements about *our best understanding* of the way things are. Most scientists believe that over time our scientific theories get closer and closer to the truth of the way things really are. But when they are speaking carefully scientists do not claim that our present understanding of this or that is the truth about this or that.

> Scientific claims are statements about our best understanding of the way things are. Hopefully, our understanding gets closer to the truth over time.

Truth vs. Facts

Whatever the truth is about the way things are, that truth is presumably absolute and unchanging. If there is a God, then that's the way it is, period. And if matter is made of atoms as we think it is, then that is the truth about matter and it is always the truth. But what we call scientific facts, by their very nature, are not like this. Facts can change, and sometimes do, as new information comes to light through ongoing scientific research. Our definitions for truth and for scientific facts need to take this difference into account. As we have seen, truth is the way things really are. By contrast, here is a definition for *scientific facts*:

> A scientific fact is a proposition that is supported by a great deal of evidence.
>
> Scientific facts are discovered by observation and experiment, and by making inferences from what we observe or from the results of our experiments.
>
> A scientific fact is *correct as far as we know*, but can change as new information becomes known.

So facts can change. Scientists do not put them forward as truth claims, but as propositions that are correct as far as we know. In other words, scientific facts are *provisional*. They are always subject to revision in the future. As scientists make new scientific discoveries, they must sometimes revise facts that were formerly considered to be correct. The truth about reality, whatever it is, may be regarded as absolute and unchanging.

> Scientific facts are provisional.

The distinction between truth and scientific facts is crucial for a correct understanding of the nature of scientific knowledge. Facts can change; truth does not.

Science

Having established some basic principles about the distinction between scientific facts and truth, we are now finally ready to define science itself and examine what science is and how it works. Here is a definition:

> Science is the process of using experiment, observation and logical thinking to build "mental models" of the natural world. These mental models are called *theories*.

We do not and cannot know the natural world perfectly or completely, so we construct models of how it works, and we explain these to one another with descriptions, diagrams and mathematics. These models are our scientific theories.

Theories never explain the world to us perfectly. To know the world perfectly we would have to know the absolute truth about reality, which we do not know. So theories always have their limits, but we hope they get better and better and more complete over time, accounting for more and more physical phenomena (facts), and helping us to understand the natural world as a coherent whole.

Scientific knowledge is continuously changing and advancing through a cyclic process that I call the *Cycle of Scientific Enterprise*, represented in Figure 1-1. In the next few sections we will examine this cycle in detail.

Theories

Theories are the grandest thing in science. In fact, it is fair to say that theories are the *glory* of science, and developing good theories is what science is all about. Electromagnetic field theory, atomic theory, quantum theory, the general

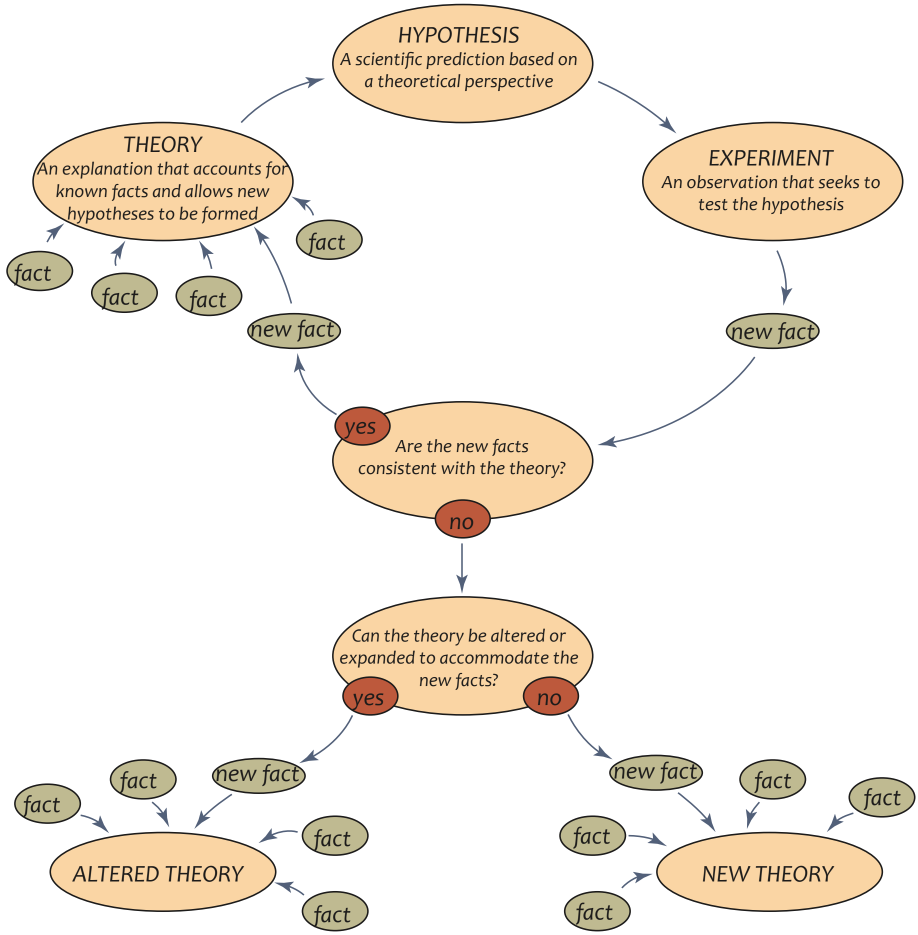


Figure 1-1. The Cycle of Scientific Enterprise.

Theories are the *glory* of science.

theory of relativity—these are all theories in physics that have had a profound effect on scientific progress and on the way we all live. Now, even though many people do not realize it, *all scientific knowledge is theoretically based.* To explain this statement we need a definition for theories, so here is mine:

A *theory* is a mental model or explanatory system that explains and relates together most or all of the facts (the data) in a certain sphere of knowledge.

A theory is not a hunch or a guess or a wild idea, even though theories are often regarded this way by the lay public. Theories are the mental structures we use to make sense of the data we have. We cannot understand any scientific data without a theory to organize it and explain it. This is why I wrote that all scientific knowledge is theoretically based.

All scientific knowledge is theoretically based.

It is inappropriate and scientifically incorrect to scorn these explanatory systems as "merely a theory" or "just a theory." It is popular in some circles to speak dismissively of certain scientific theories, or even to mock them, as if they represented some kind of untested speculation. It is simply incorrect—and very unhelpful—to speak this way. Theories are explanations that account for and connect together a lot of different facts. If a theory has stood the test of time, this means it is strongly supported by scientific evidence, it has been successful in stimulating further research, and as a result has wide support within the scientific community.

The failure to refer to theories correctly, and to understand the distinction between a theory and a truth claim, has caused a lot of confusion. To some extent, the ongoing faith vs. science debate in America is being fueled by this misunderstanding. So our public discourse could take a big step forward if the nature of scientific theories were more widely understood. For this reason, it is very important for elementary school teachers to have a

Examples of Famous Theories

There are many famous theories in modern science. Here are two examples in the field of physics:

Einstein's general theory of relativity, published in 1915, is one of the most important theories in modern physics. Einstein's theory represents our best current understanding of how gravity works.

Another famous theory we will discuss later is the Kinetic Theory of Gases, our present understanding of how molecules of gas too small to see are able to create pressure inside a container.

solid understanding of what theories are and of the critical role they play in the Cycle of Scientific Enterprise. It is also critical that elementary school teachers find ways of helping their students understand these things, too.

Let's move on now and dig a bit further into how theories work.

Characteristics of Theories

All useful scientific theories must possess several characteristics. The two most important ones are:

- The theory accounts for and explains most or all of the related scientific facts.
- The theory enables new hypotheses to be formed and tested.

Theories take decades or even centuries to form. If a theory gets replaced by a new, better theory, this also usually takes decades or even centuries to happen. No theory is ever "proved" or "disproved" and, once again, scientists do not speak this way when they are being careful. We teachers should not speak of them in this way either. We also do not speak of theories as being "true," because, as we have already seen, we do not use the term "truth" when referring to scientific knowledge. Instead we speak of facts being correct as far as we know, or of current theories as representing our best understanding, or of theories being successful (i.e., useful) models that lead to accurate predictions.

When experimental outcomes turn out the way scientists expect them to, based on their current theoretical understanding, the results are said to *support* the theory. After such an experiment the theory is stronger, but it is not proved. If a hypothesis is not confirmed by an experiment, the theory might be weakened, but it is not disproved. Scientists require a great deal of experimental evidence before a new theory can be established as the best explanation for a body of data. This is why it takes so long for theories to develop. And since no theory ever explains everything perfectly, there are always phenomena we know about that our best theories do not adequately explain. Of course, scientists continue their work in a certain field hoping eventually to have a theory that does explain all of the facts. But since no theory explains everything perfectly, it is impossible for one experimental failure to bring down a theory. Just as it takes a lot of evidence to establish a theory, so it would take a large and growing body of conflicting evidence before scientists would abandon an established theory.

> We do not speak of theories as being proved or disproved. Instead, we speak of them as being strengthened or weakened by new experimental results.

I have described theories as "mental models." This statement needs a bit more explanation. A model is a representation of something, and models are designed for a purpose. Consider the popular models of the organs in the human body often seen in science classrooms or textbooks. A model like this is a physical model, and its purpose is to help people understand how the human body is put together. By contrast, a mental model is not physical; it is an intellectual understanding, although we often use illustrations or physical models to help communicate to one another our mental ideas.

As in the example of the model of the human body, a theory is also a model. That is, a theory is a representation of how part of the world works. Frequently our models take the form of mathematical equations that allow us to make numerical predictions and calculate the results of experiments. The more accurately a theory represents the way the world works, which we judge by forming new hypotheses and testing them with experiments, the better and more successful the theory is. A solid track record of successful, accurate predictions is what makes a theory strong and leads to widespread acceptance in the scientific community.

For a scientist to subscribe to a theory means that in the view of that scientist the theory represents our best explanation for known facts in a specific area of research. As we have seen, theories evolve over time, sometimes being replaced as better or more comprehensive explanatory frameworks are conceived of and developed. This means that as with scientific facts, theories too are provisional. They represent the best understanding we have at present, and we expect them to evolve further in the future.

To summarize, a good theory represents the natural world accurately. This means the model will be useful, because if a theory is an accurate representation, then it will lead to accurate predictions about nature. When a theory repeatedly leads to predictions that are confirmed in scientific experiments, it is a good theory.

Finally, when learning about scientific facts and theories as we are here, people often ask how scientific *laws* fit in to this picture. The simplest way to think about this in a scientific context is that the term law is simply an obsolete term for a theory. All of the laws we will encounter later in this book, such as the law of conservation of energy or Newton's Laws of Motion, are simply theories. We continue using the historical names for these theories even though the term law is no longer used in scientific discourse. Isaac Newton's law of universal gravitation and Albert Einstein's theory of general relativity are both about gravity. But the statement, "Einstein's general *theory* of relativity is more accurate than Newton's *law* of universal gravitation" poses no dilemma for the scientist.

> The term *law* is simply an obsolete term for a theory.

These key points about theories are summarized in Figure 1-2.

Hypotheses

After facts and theories, the next stage in the Cycle of Scientific Enterprise is the hypothesis stage. As we saw in the previous section, good theories continue to

Key Points About Theories

- A theory is a way of modeling nature, enabling us to explain why things happen in the natural world from a scientific point of view.
- A theory attempts to account for and explain the known facts that relate to it.
- Theories must enable us to make new predictions about the natural world so we can learn new facts through experimentation.
- Successful theories are the glory and goal of scientific research.
- A theory becomes stronger by producing successful predictions that are confirmed by experiment. A theory will be gradually weakened if new experimental results repeatedly turn out to be inconsistent with the theory.
- It is incorrect to speak dismissively of successful theories, because theories are not just guesses or hunches.
- We do not speak of theories as being proved or disproved. Instead we speak of them in terms of how successful they have been at making predictions and how accurate the predictions have been.

Figure 1-2. Key points about theories.

lead to new hypotheses, enabling scientific research to continue moving forward. I prefer the following definition for *hypotheses*[1]:

A hypothesis is a positively stated, informed prediction about what will happen in certain circumstances.

We say a hypothesis is an *informed* prediction because when we form hypotheses we are not just speculating out of the blue. Every scientific hypothesis is based upon a particular theory. We are applying a certain theoretical understanding of the subject to the new situation before us and predicting what will happen or what we expect to find in the new situation based on the theory the hypothesis is coming from. Or put another way, a new hypothesis guides future research by pointing scientists in new experimental directions. As with the example

Every hypothesis is based on a particular theory.

1 These days people tend to say "a hypothesis." Fifty years ago it was considered correct to say "an hypothesis," and some people still consider this to be the most correct form. The plural is hypotheses.

Examples of Famous Hypotheses

Einstein used his general theory of relativity to make an incredible prediction in 1917: that gravity causes light to bend as it travels through space. In a later chapter we will look at the stunning result that occurred when this hypothesis was put to the test.

The year 2012 was an important year for the standard theory of subatomic physics, known as the Standard Model. This theory leads to the prediction that there are weird particles in nature called Higgs Bosons, first predicted by Peter Higgs in 1964. For fifty years scientists anticipated the day when the Higgs Boson might be experimentally observed. An enormous machine that can detect these particles, called the Large Hadron Collider, was built in Switzerland and completed in 2008. Then after several years of collecting enormous quantities of data, scientists announced on July 4, 2012 that the Higgs Boson had been detected at last, a major victory for the Standard Model. Of course, the fact of the Higgs Boson's existence is provisional, and scientists continue to collect data to support it.

hypotheses in the box above, the hypothesis is suggested by the theory itself, and leads scientists immediately to begin thinking about ways the hypothesis might be subjected to experimental verification. If Higgs Bosons do exist as the Standard Model seems to predict, how might we go about detecting them?

Often hypotheses are worded as IF-THEN statements, such as, "If various forces are applied to a pickup truck, then the truck will accelerate at a rate that is in direct proportion to the net force." (As we will see later, this hypothesis is based on the theoretical framework known as Newton's Laws of Motion.) Every scientific hypothesis is based on a theory, and it is the hypothesis that is directly tested by an experiment. If the experiment turns out the way the hypothesis predicts, the hypothesis has been confirmed, and the theory it came from is strengthened. Of course, the hypothesis may not be confirmed by the experiment. We will see how scientists respond to that situation in the next section.

The terms *theory* and *hypothesis* are often used interchangeably in common speech, but in science they mean very different things. Successful theories allow scientists to form new hypotheses that can be tested experimentally.

> In science the terms theory and hypothesis mean very different things.

This raises another important point about hypotheses. A hypothesis that cannot be tested is not a scientific hypothesis. For example, horoscopes purport to predict the future with statements such as, "You will meet someone important to your career in the coming weeks." Statements like this are so vague they are untestable, and do not qualify as scientific hypotheses.

The key points made in this section about hypotheses are summarized in Figure 1-3.

Key Points About Hypotheses

- A hypothesis is an informed prediction about what will happen in certain circumstances.
- Every hypothesis is based on a particular theory.
- Scientific hypotheses must be testable, which is what scientific experiments are designed to do.

Figure 1-3. Key points about hypotheses.

Experiments

The final step in the main circuit of the Cycle of Scientific Enterprise is to conduct experiments, which we can define as follows:

A scientific experiment is a physical arrangement for collecting data which can be used to confirm or disconfirm a particular hypothesis.

Two hundred years ago, scientists often used fairly simple experiments performed in a spare room or workshop to make important scientific advancements. But in our day, effective *experiments* are very complex and difficult to perform. Thus, for any experimental outcome to become regarded as a scientific fact it must be replicated by several different experimental teams, often working in different labs around the world.

Once confirmed, the result of an experiment gives rise to new facts. This is the case regardless of whether the hypothesis is confirmed or not. But if the outcome of an experiment does not confirm the hypothesis we have to consider all of the possibilities for why this happened. Why didn't our theory, which is our best model of the natural world, enable us to form a correct prediction? There are a number of possibilities.

- The experiment may have been flawed. Scientists will double check everything about the experiment, making sure all equipment is working properly, going over the calculations, looking for unanticipated factors that may have inadvertently influenced the outcome, verifying that the measurement instruments are accurate enough and precise enough to do the job, and so on. They will also wait for other experimental teams to try the experiment to see if they get the same results or different results, and then compare. (Although, naturally, every scientific team would like to be the first one to complete an important new experiment.)

- The hypothesis may not have been based on a correct understanding of the theory. Maybe the experimenters did not understand the theory well enough, and maybe the hypothesis is not a correct statement of what the theory says will happen.
- The input values used in the calculation of the hypothesis' predictions may not have been accurate or precise enough, throwing off the hypothesis' predictions. Or maybe the experimental results were not precise or accurate enough to allow for comparison to the predictions.
- Finally, if all else fails, and the hypothesis still cannot be confirmed by experiment, it is time to look again at the theory. Maybe the theory can be altered to account for this new fact. If the theory simply cannot account for the new fact, then the theory has a weakness, namely, that there are facts it doesn't account for adequately. If enough of these weaknesses accumulate, then over a long period of time (typically decades) the theory might eventually need to be replaced with a different theory, that is, another, better theory that does a better job of explaining all the facts we know. Of course, for this to happen someone would have to conceive of a new theory, which usually takes a great deal of scientific insight. A new theory has to account for all of the facts as well as the old theory did, and the new facts as well. This is a tall order!

Ideas for Your Classroom

1. In third grade children should begin learning how to describe facts as "correct as far as we know," and as distinct from knowledge we would call truth. Consider activities using sample statements such as those on pages 3-5. Students could first learn to distinguish statements that are true (or not true) from those that are correct as far as we know. Later students can try forming their own statements of each type.
2. In fourth grade students can begin learning in detail about what theories are and their important characteristics. Use activities in which students develop theories to explain known information, and then use their theories to predict new information. This process is the essence of the game Battleship.
3. One example of an activity that simulates the theory-hypothesis-experiment process is called *What's Your Theory?* In this activity the teacher has a hidden set of colored tiles in a predictable, geometric arrangement. The colors and locations of several tiles are divulged to the students as known data or facts. Students work in teams to construct theories regarding the unknown arrangement of tiles, and then take turns forming hypotheses and testing them out. Each negative experimental result is taken back to the theory and the theory is revised to accommodate all of the new information. For information about this activity visit the free resources page at novarescienceandmath.com.

Goals for Chapter 3

1. Define and distinguish between velocity and acceleration.
2. Explain the difference between accuracy and precision.
3. Describe the key features of the Ptolemaic model of the heavens, including all of the spheres and regions in the model.
4. State several additional features of the medieval model of the heavens and relate them to the theological views of the medieval Church.
5. Briefly describe the roles and major scientific models or discoveries of Copernicus, Tycho, Kepler, and Galileo in the Copernican Revolution. Also, describe the significant later contributions of Isaac Newton and Albert Einstein to our theories of motion and gravity.
6. Describe the theoretical shift that occurred in the Copernican Revolution.
7. Describe Kepler's Laws of Planetary Motion.
8. Describe how the gravitational theories of Kepler, Newton and Einstein illustrate the way the Cycle of Scientific Enterprise works.

About This Chapter

In addition to the physics of motion, in this chapter we are also going to review some of the history of views about the motion of the planets. There are two main reasons for integrating this material here. First, the study of motion has historically gone hand-in-hand with scientists' attempts to model the motion of the planets. So the study of motion is the perfect occasion for looking at the fascinating saga of the Copernican Revolution.

The second reason relates to one of the major topics in Chapter 1, the Cycle of Scientific Enterprise. The best way to gain a firm understanding of how this cycle continuously operates in scientific work is to see how the cycle plays out in particular historical episodes.

Chapter 3
Motion on Earth and In the Heavens

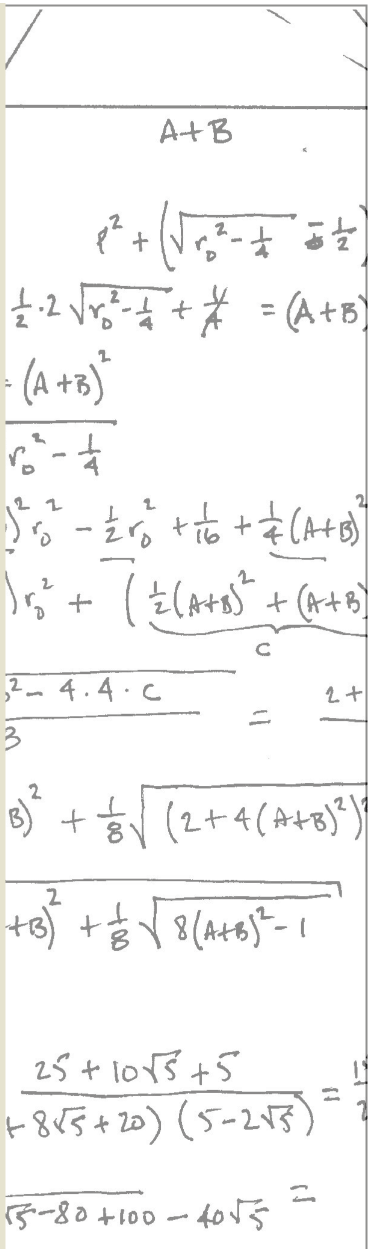
About the Mathematics

If you are apprehensive about this book because of concerns about the math, *set your mind at ease*. Yes, physics is a highly mathematical subject. As one of my favorite movies puts it, "You can't do physics without mathematics, really, can you?"

But we can, in fact, do a lot of physics without letting the math get in our way, and this will be our plan. This book is primarily a resource for teachers, and I assume that some of the teachers reading this book would like to stick to the conceptual descriptions; others may wish to see some sample calculations.

In the main body of the text I limit the mathematics to merely presenting the basic equations, variables and units of measure one might encounter in a high school freshman-level introductory physics course, without actually working through any computations. For those interested, I include a few relatively simple example problems in separate boxes. With two or three exceptions, following the solutions to these problems requires only basic skills in introductory algebra.

Also, for those interested, I have included several appendices treating mathematical topics such as unit conversions, significant digits, scientific notation, and measurement.



In the next couple of sections we will touch lightly on some issues involved with measurements such as units of measure, accuracy and precision. For a fuller treatment of these and other matters see the Appendices.

Unit Systems and MKS Units

Units of measure are crucial in science. Science is about making measurements, and a measurement without units of measure is a meaningless number. The two major systems for units of measure are the SI (from the French *Système international d'unités*), typically known in the United States as the metric system, and the USCS (U.S. Customary System) with which all Americans are familiar.

The USCS is very cumbersome, and not especially useful for scientific work. One problem is that there are many different units of measure for every kind of physical quantity. Just for measuring distance, for example, we have the inch, foot, yard, and mile. The USCS is also full of random numbers like 3, 12 and 5,280, and there is no inherent connection between units for different types of quantities.

By contrast, the SI system is simple and has many advantages. There is one basic unit of measure for each kind of quantity, such as the meter for measuring length. Instead of having a bunch of different unrelated units of measure for measuring quantities of different sizes, prefixes based on powers of ten are used on all of the units to accommodate different sizes of measurements. And units for different types of quantities relate to one another in some way. Unlike the gallon and the foot, which have nothing to do with each other, the liter[1] is 1,000 cubic centimeters. For all of these reasons the USCS is not used much in scientific work. The SI system is the international standard and students should be exposed to it early and often.

A subset of the SI system is the *MKS system*. The MKS system uses the *meter*, the *kilogram*, and the *second* (hence, "MKS") as primary units. There are also four other primary units, some of which we will encounter later on. There are also many derived units that are combinations of these three primary units. Examples of derived units that we will encounter in this book are the newton (N) for measuring force, the joule (J) for measuring energy, and the watt (W) for measuring power.

Dealing with different systems of units can become very confusing. But the wonderful thing about sticking to the MKS system is that any calculation performed with MKS units will give a result in MKS units. This is why the MKS system is so handy and why calculations in physics make use of it almost exclusively.

> In the MKS System of units (meter-kilogram-second), any computation undertaken with values expressed in MKS units will produce a result in MKS units.

1 Technically, the liter is not an official SI unit of measure. It is, however, commonly used as a metric unit in scientific work.

For more information about the SI system, refer to Appendix D.

Accuracy and Precision

Science is all about investigating nature and to do that we must make measurements. In the study of science the terms *accuracy* and *precision* are technical terms that refer to the limitations inherent in making measurements. These terms are often used interchangeably in common speech, but in the context of measurement they have specific, distinct meanings. Accuracy may be defined as follows:

Accuracy refers to freedom from error in a measurement. The lower the error, the more accurate the measurement.

The error in a measurement is the difference between the value of a quantity obtained from a measurement and the actual, true value of the quantity. The lower the error in a measurement, the better the accuracy. There are many potential sources of error in measurements, including human mistakes, malfunctioning equipment, incorrectly calibrated instruments, or lurking variables. All measurements contain error, because (alas!) perfection is simply not a thing we have access to in this world.

Precision may be defined as follows:

Precision refers to the resolution in a measurement, indicated by the number of significant digits in the value of the measurement.

The term *precision* refers to the resolution or degree of "fine-ness" in a measurement. The limit to the precision that can be obtained in a measurement is ultimately dependent on the instrument being used to make the measurement. If one wants greater precision, one must use a more precise instrument. The precision of a measurement is indicated by the number of *significant digits* included in the value when the measurement is written down.

An example will illustrate the difference between accuracy and precision. Let's say Shana and Marius each buy digital thermometers for their homes. The thermometer Shana buys cost \$10, and measures to the nearest 1°F. Marius pays \$40 and gets one that reads to the nearest 0.1°F. Shana reads the directions and properly installs the sensor for her new thermometer in the shade. Marius doesn't read the directions and mounts his sensor in the direct sunlight, which causes a significant error in the measurement for much of the day. The result will be that Shana has lower-precision, but higher-accuracy measurements!

For a more complete description of how significant digits work, see Appendix B.

Motion, Velocity and Acceleration

In this book we will examine two types of *motion*: motion at a constant *velocity*, when an object is not accelerating, and motion with a *uniform acceleration*. Defining these terms is a lot simpler if we stick to motion in one dimension, that is, motion in a straight line. So in this book this is what we will do. With this simplification we can define velocity as follows:

To keep our discussion both simple and accurate, we will consider only motion in a straight line.

The velocity of an object is the rate at which the distance to where it started is changing.

Thus, a girl walking at a velocity of three miles per hour is increasing the distance between herself and where she started at a rate of three miles every hour.

Note that an object's velocity is a measure of how fast the object is going, *not* whether its velocity is changing or not. When the velocity of an object is not constant the object is *accelerating*. This gives us the following definition for acceleration:

The acceleration of an object is the rate at which the object's velocity is increasing or decreasing.

If an object's velocity is increasing or decreasing at a constant rate, as in the case of a falling object, we say the acceleration is *uniform*. In this book we will consider only situations involving constant velocity or uniform acceleration. (Calculus is required to solve problems in which the acceleration is not uniform. We will leave that for some other book.) One way to rephrase our definition for acceleration would be to say that if an object is not accelerating it must be either at rest or moving with a constant velocity.

If an object is not accelerating it must be either at rest or moving with a constant velocity.

As an aside, the terms "at rest" and "moving with a constant velocity" refer to two different "states of motion." This state-of-motion language is important for a very good reason: Isaac Newton. Newton's Laws of Motion are universally studied by all students of physics. And Newton's First Law of Motion, which we will get into in the next chapter, makes use of this language.

There are two important equations used for solving problems involving motion with a constant velocity or motion with uniform acceleration. One equation is for motion at a constant velocity, and the other is for motion with uniform acceleration. For motion with a *constant velocity*, the equation is

$$d = vt$$

where d is the distance an object travels in meters (m), v is the object's velocity in meters per second (m/s) and t is time interval in seconds (s).

Note here that using the MKS units of meters and seconds for the distance and the time, the MKS units for velocity will be meters per second (m/s). We can see this by taking the equation above and dividing both sides by t, giving

$$\frac{d}{t} = \frac{vt}{t} = v$$

$$v = \frac{d}{t}$$

Since velocity is calculated as distance divided by time, the units for velocity will be the distance units divided by the time units, or meters per second (m/s).

For the case of uniform acceleration we calculate the acceleration over a specific interval of time. We call the velocity at the beginning of the time interval the initial velocity, symbolized v_i. The velocity at the end of the time interval is the final velocity, v_f. The time interval is simply denoted t, as in the equation above for constant velocity motion.

The equation we use to calculate uniform acceleration in terms of the initial final velocities is

$$a = \frac{v_f - v_i}{t}$$

where a is the acceleration in units of meters per second squared (m/s^2).

Example Problem

Sound travels approximately 342 m/s in air. At this velocity, how far will the sound from the starter pistol at a race travel in 0.0500 s?

The given quantities are

$$v = 342\ \frac{\text{m}}{\text{s}}$$
$$t = 0.0500\ \text{s}$$

Inserting these into the distance equation and solving we have

$$d = vt = 342\ \frac{\text{m}}{\text{s}} \cdot 0.0500\ \text{s} = 17.1\ \text{m}$$

The MKS unit for acceleration, meters per second squared (m/s²), often drive people crazy until they get their brains wrapped around it, so we will pause here and discuss it. (Then you can sleep peacefully tonight.) We noted just above that the acceleration is the rate at which the velocity is changing. The acceleration simply means that the velocity is increasing or decreasing by so many meters per second, every second. Now, the terms "per" and "every" in the preceding sentence indicate fractions, and if a velocity is changing so many meters per second, every second, we would write these units in a fraction this way and simplify the expression using the "invert and multiply" rule for dividing fractions:

$$\frac{\frac{\mathrm{m}}{\mathrm{s}}}{\mathrm{s}}=\frac{\frac{\mathrm{m}}{\mathrm{s}}}{\frac{\mathrm{s}}{1}}=\frac{\mathrm{m}}{\mathrm{s}}\cdot\frac{1}{\mathrm{s}}=\frac{\mathrm{m}}{\mathrm{s}^2}$$

So the $\mathrm{m/s^2}$ units for acceleration are really no mystery. If we subtract two velocities we get a velocity. And if we divide that velocity by time, we get $\mathrm{m/s^2}$.

We must be very careful to distinguish between velocity (m/s) and acceleration ($\mathrm{m/s^2}$). Acceleration is a measure of how fast an object's velocity is changing, not

Example Problem

A truck is moving with a velocity of 18.8 m/s when the driver hits the brakes and brings the truck to a stop. The total time required to stop the truck is 8.75 s. Determine the acceleration of the truck, assuming the acceleration is uniform.

We note that since the truck stopped, the final velocity is zero. Writing down all the given quantities,

$$v_i = 18.8\ \frac{\mathrm{m}}{\mathrm{s}}$$
$$v_f = 0$$
$$t = 8.75\ \mathrm{s}$$

Now we place these quantities into the equation for acceleration and solve the problem.

$$a=\frac{v_f-v_i}{t}=\frac{0-18.8\ \frac{\mathrm{m}}{\mathrm{s}}}{8.75\ \mathrm{s}}=-2.15\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

The negative sign in this result simply means that the trucking is slowing down.

how fast it is going. To help emphasize the difference, note that an object can be at rest ($v = 0$) and accelerating at the same instant!

Now, although this may not be at all clear at first, it is very important to think this through and understand how this counter-intuitive situation can come about. Here are two illustrations. Every time an object starts from rest, such as the instant when the driver hits the gas while sitting at a traffic light, the object will be simultaneously at rest and accelerating. This is because if an object at rest is to ever begin moving its velocity must *change* from zero to something else. In other words, the object must accelerate. Of course, this situation only holds for an instant; the velocity instantly begins changing and does not stay zero.

Perhaps this point will be easier to see with this second illustration. As depicted in Figure 3-1, when a ball is thrown straight up and reaches its highest point it must stop for an instant before coming back down. At its highest point the ball is simultaneously at rest and accelerating. As before, this situation only holds for a single instant.

The point of these two illustrations is to emphasize the difference between the two variables we are discussing, velocity and acceleration. If an object is moving at all, then it has a velocity that is not zero. The object may or may not be accelerating. But acceleration is about whether the velocity itself is changing or not. If the velocity is constant, then the acceleration is zero. If the object is speeding up or slowing down, then the acceleration is not zero.

Historically, the study of motion was closely related to the study of the motions of the planets. So for the rest of this chapter we will survey the scientific thinking of the past 2,500 years on this subject. It is quite a story!

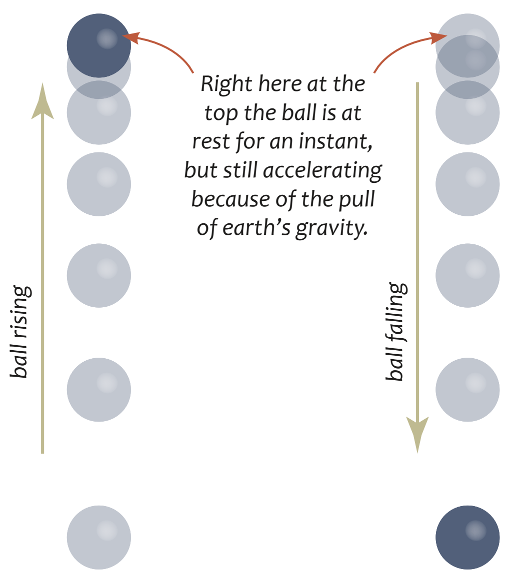


Figure 3-1. A rising and falling ball.

Crisis: What Happens When Theories are Mistaken for Truth

The view people had of the planets and stars in the medieval period began back with the Greek philosophers Plato and Aristotle in the fifth and fourth centuries BC. The famous Alexandrian astronomer Ptolemy (Figure 3-2) worked out a detailed mathematical system for this model in the second century AD. Over the next thousand years this model of the heavens was adopted by everyone in the West, including the Christian Church. Unfortunately, the Church adopted this model as the *truth*, and not as a model that could change when new information came to light. This error led to an increasing crisis as more and more discoveries seemed to conflict with Ptolemy's model.

Figure 3-2. Ptolemy of Alexandria.

This led to the Copernican Revolution, and over the course of 150 years the Ptolemaic model completely collapsed. The reason we study the Ptolemaic model now is that the history of how it developed and how it crashed is a world-class example of how science works through theories to model nature.

Seeing the Heavens from an Ancient Point of View

We will consider some of the mechanical details of Ptolemy's model soon, but before we do we need to consider a few things about the way the motion of the planets in the night sky appears to observers on earth. Now, to you and I, who all grew up in a time when it is quite clear that the planets and the earth orbit the sun, it seems obvious to us that day and night are caused by the earth's rotation on its axis. We have heard about this all of our lives.

But stop and consider how things would appear if all we had to go on was our simple observations. It does *appear* that everything is orbiting around the earth while the earth sits still, doesn't it? Don't the sun and moon rise each day and track across the sky and set? Don't the planets and stars all do the same thing? Also, it doesn't feel at all like earth is moving or rotating. We all know that anytime we spin in a circle, like people on a merry-go-round, we have to hold on to keep from falling off. We can also feel the wind in our hair. Again, if we had something with us on the merry-go-round that was tall and flexible, like a sapling, it would not stay vertical when it is moving in a circular fashion like this. Instead, it would bend over because of the acceleration pulling it in its circular motion.

These principles seemed *obvious* to *everyone* before 1500, and to everyone except a few cutting-edge astronomers right up to 1642 when Galileo died. Only a crazy person would imagine that the earth was spinning. They all knew that the earth was huge—Eratosthenes had made a very accurate estimate of the earth's circumference as far back as 240 BC. So if something that big were spinning in a circle once a day the people on its surface would be moving very fast (1,000 miles per hour on the equator, actually!) and we would have to be hanging on for dear life! The trees would be laying down, and we would be constantly feeling winds that would make a hurricane feel like a calm summer day! People used these arguments all the way up until the time of Galileo to prove that there was no way the earth was orbiting the sun and spinning around on an axis once a day. And back then these were very persuasive arguments.

Only a crazy person would imagine that the earth was spinning.

Retrograde Motion

To understand the reason for some of the features of Ptolemy's model we need to take a quick look at the phenomenon known as *retrograde motion*. If a person goes out and looks at, say, Mars each night and makes a note of its location against the stars, she will see that Mars appears in a slightly different place each night. The planet will gradually work its way along a pathway against the starry background night after night. If our observer tracks the planet for several months or a year it will move quite far. Moreover, there will be periods of time lasting several weeks when the nightly progress of the planet reverses course. Mars appears to be backing up! This apparent backing up is called retrograde motion.

Nowadays we easily explain the movement of the planets in the sky, as well as retrograde motion, by looking at the geometry of where earth is and where the planets are as we all orbit around the sun. No planet actually reverses course in its orbit, but depending on where earth is and where a planet is (on the same side of the sun, on opposite sides of the sun, and so on) a given planet will appear to be moving one direction or another relative to the stars.

But in the Ptolemaic model the earth is stationary. All of the planets, and the sun as well, orbit around the earth, not the sun. Additionally, the heavenly bodies move together, all rotating around the earth once each day. This makes the smaller motion of the planets, and their retrograde motions, harder to explain. Ptolemy explained it by assuming the planets all moved in *epicycles*. An epicycle is a circular path around a center point, and the center point itself travels on a circular path around the earth. Figure 3-3 depicts a planet moving in a path defined by an epicycle. The motion of a planet moving on an epicycle would be like that of a person in the "tea cup" ride at an amusement park.

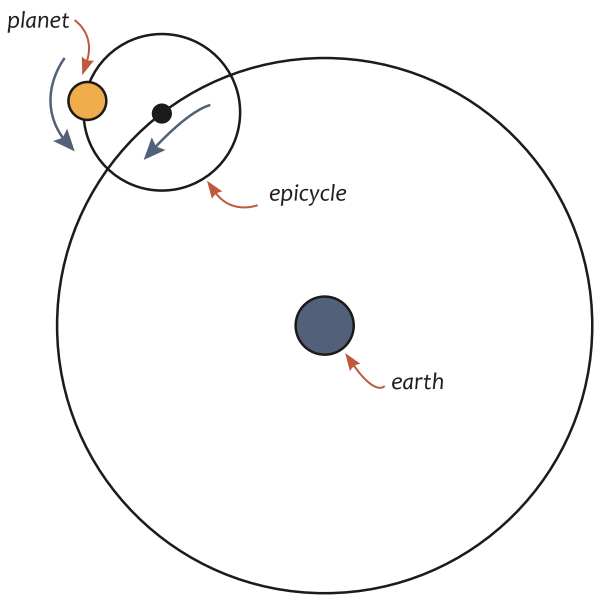


Figure 3-3. A planet moving in a path defined by an epicycle around the earth.

The Medieval Model of the Heavens

The prevailing model of the heavens continued to be the Ptolemaic model for a very long time, right up into the mid-seventeenth century. The basic features of the Ptolemaic model included these:

- There are seven heavenly bodies: the moon, Mercury, Venus, the sun, Mars, Jupiter and Saturn.
- All heavenly bodies are perfectly spherical.
- All heavenly bodies move in circular orbital regions, called spheres.
- All of the spheres are centered on the earth, making this system a *geocentric* system.
- Corruption and change only exist on earth. All other places in the universe, including all the heavenly bodies and stars, are perfect and unchanging.
- All of the spheres containing the heavenly bodies and all the stars rotate completely around the earth every 24 hours.
- Scores of epicycles are used to explain retrograde motion.
- The heavenly bodies inhabit spheres around the earth where their orbits are. In the model there are nine spheres plus the region beyond the spheres. The first seven spheres contain the heavenly bodies. The arrangement of the spheres is as follows: